

Three questions on Lorentz violation¹

Alfredo Iorio^{a,b}

^a *Institute of Particle and Nuclear Physics, Charles University
V Holesovickach 2, 180 00 Prague 8 - Czech Republic*

^b *Department of Physics, University of Salerno
Via Allende, 84081 Baronissi (SA) - Italy*

Abstract

We review the basics of the two most widely used approaches to Lorentz violation - the Standard Model Extension and Noncommutative Field Theory - and discuss in some detail the example of the modified spectrum of the synchrotron radiation. Motivated by touching upon such a fundamental issue as Lorentz symmetry, we ask three questions: What is behind the search for Lorentz violation? Is String Theory a physical theory? Is there an alternative to Supersymmetry?

¹Invited lecture at DICE2006 Piombino - Italy, September 11-15, 2006

1 Introduction

The Special Theory of Relativity (STR) is again the subject of an intense investigation. The first time such a scrutiny took place was about one hundred years ago, when the theory was first proposed by Einstein. At that time STR represented a brilliant theoretical solution to many crucial experimental questions: the experiments - for instance those on the “luminiferous aether” - were calling for a theoretical revolution, that more or less punctually came.

It is interesting to read how eminent scientists of the time reacted to STR. For instance, it is quite noticeable the heroic effort of Bridgman - an experimentalist and Nobel laureate - to avoid to future physicists (us) another cultural shock of the kind that struck scientists with STR - and Quantum Mechanics (QM) - in the early 1900's [1]. Such an effort, although not really successful regarding the main goal of Bridgman, gave origin to a method of philosophical investigation on the meaningfulness of scientific theories that today goes under the name of *operationism*. It is surprising to learn that even Mach, who with his critics to mechanicism paved the way on the philosophical side to STR, was skeptic with Einstein's theory [2]. But skeptics had to surrender to the enormous amount of experimental evidences from a great variety of different kind of phenomena. Thus STR is probably the most solidly tested and deeply rooted theory in contemporary particle physics.

Despite STR's experimental robustness, nowadays is happening somehow the reverse of what happened at the beginning of the last century: theoretically posited questions eagerly call for experimental findings that *violate* STR. That a theory calls for experiments to prove (or disprove) its assertions it is certainly not new in physics. To a great extent already STR, and more evidently the General Theory of Relativity (GTR), are examples of this. We may even say that it is the goal of any good theoretical physicist to produce a theory that predicts unknown phenomena while keeping explaining the known ones.

Nonetheless, the search going on these days for experimental signatures of violation of Lorentz symmetry motivates, in our view, some general reflections on contemporary “theoretical particle physics”, i.e. of a large - perhaps the dominant - part of what on the Los Alamos archives goes under the name of HEP-TH. Thus, since many available reviews on Lorentz violation

are masterly written² we shall try here to do the reviewer's job in a different perspective by trying to spell out some basic issues behind the search for Lorentz violation.

2 A bird's-eye-view on the search for Lorentz violation

It is true that way after the experimental establishing of STR there have been various attempts to modify aspects of STR in various ways. Already Heisenberg questioned the causality structure of Quantum Field Theory (QFT) while facing the problem of the very definition of elementary particle [4]. On the other hand - although the paper that probably pioneered the field now known as "Lorentz violation" is that of 1990 by Carroll, Field and Jackiw³ [5] - the contemporary systematic assault to Lorentz symmetry can be ascribed to results of String Theory (ST).

The first result is Kostelecky and Samuel's discovery that in (an open bosonic, and possibly other) ST(s) Lorentz symmetry can be spontaneously broken due to the presence in the string (field) lagrangian of cubic terms that include one scalar (the tachion) and two tensor fields (of any rank) [6]. The resulting low-energy limit theory is what Colladay and Kostelecky later called the Standard Model Extension (SME) [7]. The SME is certainly the most widely used theoretical frame within which Lorentz violating phenomenological scenarios are investigated today (for a review see, e.g., [8]).

The second result is of Seiberg and Witten who discovered that a particular low-energy limit of ST leads to certain noncommutative (in the sense of spatiotemporal coordinates, e.g. $[x_\mu, x_\nu] = i\theta_{\mu\nu}$) field theories (NCFTs) [9]. They proved that these theories, although Lorentz symmetry violating, still keep standard gauge invariance. This was done by providing a map that gives the noncommutative nonlocal gauge field (transforming under the noncommutative gauge transformations) in terms of the standard commutative local gauge field (transforming under the usual gauge transformations) and

²Among the many excellent reviews on the ongoing search for Lorentz violation see, for instance, the one by Mattingly [3] where an effort is made towards including all theoretical approaches as well as the phenomenological analysis.

³There the authors introduced a Lorentz violating term of Chern-Simons origin into Maxwell electrodynamics and extensively studied the possibility of visible signatures.

of the noncommutative parameters $\theta_{\mu\nu}$. This map is known as the Seiberg-Witten (SW) map⁴. This is probably the second most used theoretical frame to study Lorentz violation⁵ (for a very recent overview see for instance the Introduction of [13]).

The SME and the NCFTs, both “string-inspired” models, are not the only two known approaches to Lorentz violation available today. We single out these two because they are the most widely used and because their explicit goal is to propose that Lorentz violation could be a fact of nature. Another available approach where Lorentz violation is posited as a fact of nature, is that of Double Special Relativity (DSR) proposed by Amelino-Camelia in [14] (see also [15]), based on *two* invariants: the speed of light and an energy scale. An important independent work is that of Coleman and Glashow that do not take that view [16]. Their idea is to *test* STR by studying what sort of new bounds can be obtained at high energies using the hypothesis that Lorentz symmetry is not exactly satisfied as a working technical tool. Others approaches also exist [3].

Let us now enter a bit more into the details of the SME and NCFTs. As said, the SME is based on a mechanism of spontaneous breaking of Lorentz symmetry within a higher dimensional string field theory. “Over there” lagrangians contain interactions that include tensor fields of any rank, hence an infinite number of them is possible. Lorentz symmetry exactly holds - where by “exact” here we mean that the lagrangian and the vacuum configuration are both symmetric - and similarly for gauge symmetry and renormalizability. This is one of the magic things of ST: such interactions would spoil gauge symmetry and renormalizability in a four dimensional field theory, but for higher dimensional strings this is not a problem. One such stringy interactions is a cubic term with a scalar and a squared tensor field. For stability the vacuum expectation value (vev) of this scalar field cannot be zero, thus

⁴It is surely possible to construct gauge theories on noncommutative spaces such that the SW map holds without direct reference to ST, as shown in [10] where the authors consider $[x, \cdot]$ as a derivative and make this derivative gauge covariant. What we want to stress here, though, is the profound impact on the HEP-TH community and beyond of ideas originated in ST: would the Seiberg-Witten map be discovered without Seiberg and Witten?

⁵The quantum phase of NCFTs is still an open issue: it was shown that novel infrared divergencies appear in such theories [11], but whether these are unavoidable or not is still to be clarified. Lately it was argued that such divergencies should not be present if noncommutativity is implemented via a deformed (twisted) coproduct [12].

giving rise to a nonzero mass for the tensor fields that this way have nonzero vevs. As the tensors transform non trivially under the Lorentz group this mechanism gives rise to a spontaneous breaking of such symmetry. As for any spontaneous breaking, it is the vacuum configuration that becomes not symmetric, while the lagrangian remains so. By the usual mechanism of the shifting/redefinition of the fields (the rescaling of the vacuum to the “true” vacuum) the vevs of these fields, say $C_{\mu\dots\nu}^{(k)}$, appear in the lagrangian.

In the SME the breaking is chosen so that such coefficients combine with the fields of the SM (and gravity) and their derivatives. The Lorentz (and possibly CPT) violating terms *added* to the SM terms have then the form

$$C_{\mu\dots\nu}^{(k)}(\text{SM fields and derivatives})^{\mu\dots\nu}, \quad (2.1)$$

where $C^{(k)} \sim 1/m_{\text{Planck}}^k$, so that the higher we go with the power k , the smaller the effect. Notice here the appearance of the fundamental length $\ell_{\text{Planck}} \sim m_{\text{Planck}}^{-1}$.

The idea here is to find phenomenological setups such that the “Planck size” effects can be “magnified” to the point of giving rise to signatures measurable by the instruments at our disposal. Those effects should have visible signatures “over here”, i.e. at reachable energy scales too. This is quite an interesting point of view. It is somehow opposed to the idea that it is impossible to test phenomena that take place at the Planck scale. Of course, it is not claimed that this way one reaches the “Planck world”, but the core of the approach, so to speak, is that the “Planck world” and “our world” cannot be fully decoupled.

It is crucial to notice that the Lorentz indices match: the Lorentz violating terms do not violate the symmetry explicitly (as, for instance, a non-matching index would brutally do) but they are still scalars when *all* the terms, the $C^{(k)}$ s and the SM fields and derivatives, are transformed. On the contrary, when the $C^{(k)}$ s are *not* transformed (as one would expect, for instance, if these terms would represent a fixed background) then Lorentz violation comes about. This occurrence is usually referred to as: The SME is “observer-Lorentz” invariant, while it is “particle-Lorentz” violating, the “observer” transformations being those of the first kind - i.e. those involving the coefficients *and* the fields - the “particle” transformations being those of the second kind.

This model brings with it many nice features of the original ST model: it is powercounting renormalizable, gauge invariant, P_μ is conserved and

$P_0 > 0$. These properties made SME's success and the various $C^{(k)}$ s for the different sectors of the SME (especially those in the electromagnetic sector) have been cleverly searched for in a great variety of experiments and experimental proposals (see e.g. [8]).

We want to discuss now the example of the spectrum of the synchrotron radiation to give a flavor of the kind of modifications one encounters by dealing with Lorentz violation and to make explicit one of the mechanisms by which “amplification” of Planck-size effects can take place. We shall not present the SME treatment but instead we shall treat the case within a noncommutative electrodynamics (NCED) approach⁶. This will also give us the chance to introduce some details on the basic formalism of NCFTs approach.

Suppose that, due to a fundamental length $\ell_{\text{string}} \sim \sqrt{\theta} \sim \ell_{\text{Planck}}$, spatiotemporal coordinates do not commute. One way of making this explicit is⁷

$$x^\mu * x^\nu - x^\nu * x^\mu = i\theta^{\mu\nu} , \quad (2.2)$$

where the (Moyal-Weyl $*$ -)product of any two fields $\phi(x)$ and $\chi(x)$ is defined as $(\phi * \chi)(x) \equiv e^{\frac{i}{2}\theta^{\mu\nu}\partial_\mu^x\partial_\nu^y}\phi(x)\chi(y)|_{y \rightarrow x}$, and it is a suitable generalization of the multiplication law in the presence of a nonzero θ . Finally, $\theta^{\mu\nu}$ is c -number valued, constant, and the Greek indices run from 0 to 3. The NCED action is

$$\hat{I} = -\frac{1}{4} \int d^4x \hat{F}^{\mu\nu} \hat{F}_{\mu\nu} , \quad (2.3)$$

where $\hat{F}_{\mu\nu} = \partial_\mu \hat{A}_\nu - \partial_\nu \hat{A}_\mu - i[\hat{A}_\mu, \hat{A}_\nu]_*$. As said, the nonlocal field \hat{A}_μ can be expressed in terms of a standard U(1) gauge field A_μ and of $\theta^{\mu\nu}$ by means of the SW map⁸ [9] $\hat{A}_\mu(A, \theta)$, that at $O(\theta)$ reads

$$\hat{A}_\mu(A, \theta) = A_\mu - \frac{1}{2}\theta^{\alpha\beta} A_\alpha (\partial_\beta A_\mu + F_{\beta\mu}) . \quad (2.4)$$

⁶To a certain extent NCFTs can be seen as a SME with a particular choice of the coefficients $C_{\mu\dots\nu}^{(k)}$ [3], [8],[17].

⁷Of course, this is not the most general way noncommutativity of the coordinates could take place. For instance, two equally valid, if not more general, approaches are the Lie-algebraic and the coordinate-dependent (q -deformed) formulations [10], and many other approaches exist. Nonetheless, the canonical form is surely the most simple and the basic features of noncommutativity are captured in this model.

⁸ $\hat{A}_\mu(A, \theta) \rightarrow A_\mu$ as $\theta^{\mu\nu} \rightarrow 0$, hence, in that limit, $\hat{F}_{\mu\nu} \rightarrow F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$.

The Noether currents for space-time transformations of the theory (2.3) are $J_f^\mu = \Pi^{\mu\nu} \delta_f A_\nu - \hat{\mathcal{L}} f^\mu$, where $\Pi^{\mu\nu} = \delta \hat{\mathcal{L}} / \delta \partial_\mu A_\nu$, and for translations (the only symmetric case) $f^\mu \equiv a^\mu \equiv \text{const.}$ Hence the (conserved) energy-momentum tensor $T^{\mu\nu} = \Pi^{\mu\rho} F_\rho^\nu - \eta^{\mu\nu} \hat{\mathcal{L}}$ is in general not symmetric, a clear sign of the breaking of Lorentz symmetry [18]. Conservation of $T^{\mu\nu}$ means conservation of the Poynting vector

$$\vec{S} = \frac{c}{4\pi} \vec{D} \times \vec{B} = \frac{c}{4\pi} \vec{E} \times \vec{H}, \quad (2.5)$$

where $D^i \equiv \Pi^{i0}$ and $H^i \equiv \frac{1}{2} \epsilon^{ijk} \Pi_{jk}$ are the constitutive relations containing all the relevant information about the Lorentz violating vacuum.

The effects of a nonzero θ , if any, are very small, thus the $O(\theta)$ model would do the job

$$\hat{I} = -\frac{1}{4} \int d^4x [F^{\mu\nu} F_{\mu\nu} - \frac{1}{2} \theta^{\alpha\beta} F_{\alpha\beta} F^{\mu\nu} F_{\mu\nu} + 2\theta^{\alpha\beta} F_{\alpha\mu} F_{\beta\nu} F^{\mu\nu}] + J_\mu \hat{A}^\mu, \quad (2.6)$$

where the vector field is coupled to an external current, and the $O(\theta)$ SW map and $*$ -product are used. In the presence of a background magnetic field \vec{b} , and for $J_\mu = 0$, the plane-wave solutions exist [19]. The waves propagating transversely to \vec{b} travel at the modified speed $c' = c(1 - \vec{\theta}_T \cdot \vec{b}_T)$ (where $\vec{\theta} \equiv (\theta^1, \theta^2, \theta^3)$, with $\theta^{ij} = \epsilon^{ijk} \theta^k$, and $\theta^{0i} = 0$) while the ones propagating along the direction of \vec{b} still travel at the usual speed of light c .

Plane-waves do not represent a case where “amplification” of the nonzero θ effects can take place. Synchrotron radiation, instead, is a case where ultrarelativistic “magnification” of the electromagnetic field in the direction of motion could help. With these ideas in mind the authors of [20] studied the synchrotron radiation in NCED, and indeed found the amplification they were looking for. It is matter of solving the modified Maxwell equations descending from (2.6) with the settings: a) charged particle moving (circularly) in the plane (1, 2): $J_\mu = ec\beta_\mu \delta(x_3) \delta^{(2)}(\vec{x} - \vec{r}(t))$, where $\vec{r}(t)$ is the position of the particle, and $\beta_\mu = (1, \vec{v}/c)$; b) $\vec{b} = (0, 0, b)$; c) $\vec{\theta} = (0, 0, \theta)$. Keeping only contributions of order $O(e/R)$, where R is the distance from the source, one can compute the electric and magnetic fields that have quite involved

expressions⁹.

To compute the spectrum in the ultra-relativistic regime ($\beta = v/c \rightarrow 1$) and far from the source ($|\vec{x}| \sim R \gg |\vec{r}(t)|$) one needs the power radiated in the direction \vec{n} : $dP(t)/d\Omega = R^2[\vec{S} \cdot \vec{n}] \equiv |\vec{L}(t)|^2$, where all the quantities ($\vec{n}, \vec{\beta}, \dot{\vec{\beta}}, R$) are in the plane (1, 2), and the Poynting vector \vec{S} given in (2.5) contains all the relevant information. In the ultra-relativistic approximations two are the characteristic frequencies for the synchrotron: the cyclotron frequency $\omega_0 \sim c/|\vec{r}|$, and the critical frequency $\omega_c = 3\omega_0\gamma^3$. For radiation in the plane the relevant range of frequencies is $\omega \gg \omega_0$ (such that the latitude $\vartheta \sim \pi/2$), hence the leading terms for the energy $dI(\omega)/d\Omega \equiv 2|\vec{L}(\omega)|^2$ (where $\vec{L}(\omega)$ is the Fourier transformed of $\vec{L}(t)$) are

$$\frac{d}{d\Omega}I(\omega) \sim \frac{e^2}{3\pi^2c} \left(\frac{\omega}{\omega_0}\right)^2 \gamma^{-4} \left[K_{2/3}^2(\xi)[1 + \lambda(1 + 6\gamma^2)] + \lambda \frac{24\gamma^5\omega_0}{\omega} K_{1/3}(\xi)K_{2/3}(\xi) \right], \quad (2.7)$$

where $\xi = (\omega/3\omega_0)\gamma^{-3}$, and $K_{2/3}(\xi)$ and $K_{1/3}(\xi)$ are modified Bessel functions¹⁰. For $\omega_0 \ll \omega \ll \omega_c$, i.e. $1 \ll \omega/\omega_0 \ll \gamma^3$,

$$X \equiv \frac{dI(\omega)/d\Omega}{dI(\omega)/d\Omega|_{\lambda=0}} \sim 1 + 10(\omega_0/\omega)^{2/3}\lambda\gamma^4. \quad (2.8)$$

This shows how the smallness of the factor $\lambda = 2\theta b$ is compensated by the fourth power of γ , hence the amplification one was looking for. For instance, by using the bound in [22], $\theta < 10^{-2}(\text{TeV})^{-2}$, one has that $\lambda = 2b\theta < 2n10^{-23}$, where n is the value of b in Tesla, and 1 Tesla $\sim 10^{-21}(\text{TeV})^2$. Thus

⁹The part proportional to $\lambda \equiv 2\theta b$ contains a term of the form

$$\left[\frac{1}{c(1 - \vec{n} \cdot \vec{\beta})} \frac{d}{dt'} \left(\frac{1}{c(1 - \vec{n} \cdot \vec{\beta})} \frac{d}{dt'} \frac{\vec{n}c(t - t')}{(1 - \vec{n} \cdot \vec{\beta})R} \right) \right]_{\text{ret}},$$

where $\vec{n} = \vec{R}/R$, and $[\]_{\text{ret}}$ are the usual retarded quantities. We see here contributions proportional to the *derivative* of the acceleration. The $\dot{\vec{\beta}}$ contribution arises as an effect of the conversion of the two speeds of lights c and c' in the poles of the Green functions into a single speed c with a *derivative* of the delta function $\delta'(\tau - R/c)$. These terms recall the familiar scenario of the Abraham-Lorentz pre-acceleration effects for the classical self-energy of a point charge [21].

¹⁰When $\omega \ll \omega_c$, for $\xi \rightarrow 0$, $K_\nu(\xi) \sim \xi^{-\nu}$, $\nu = 2/3, 1/3$.

for an electron synchrotron the correction is

$$X < 1 + \left(\frac{\omega_0}{\omega}\right)^{2/3} n \times 10^{-21} \times \left(\frac{\mathcal{E}(\text{MeV})}{\text{MeV}}\right)^4, \quad (2.9)$$

where \mathcal{E} is the energy of the electron, $\gamma_{\text{max}} \sim 2\mathcal{E}(\text{MeV})/\text{MeV}$. For the most energetic synchrotron (SPring-8, Japan) $\mathcal{E} = 8 \text{ GeV}$, $b \sim 1 \text{ Tesla}$, and when $\omega/\omega_0 \sim \gamma^2$ we have¹¹

$$X < 1 + 10^{-10}.$$

We see a “ 10^{13} -amplification” of the effects induced by a nonzero θ , independent from the actual input value for θ : from 10^{-23} to 10^{-10} in this case.

Other investigators have also looked into the synchrotron radiation within the SME [24] and other approaches [25]. They find similarly important departures from the Lorentz preserving formula in agreement with the above presented modification of the energy spectrum and with a previously proposed formula for the maximum frequency based on kinematical general arguments [26].

Synchrotron radiation is just one among the many phenomenological setups (a large part of which in the electromagnetic sector) that have been lately investigated, and we make here no claim that it is the most important. We picked up this example because it clarifies the amplification mechanism quite cleanly and because of our own familiarity with it. Despite the growing number of phenomenological/experimental investigations, no signals of violation are found. In the most fortunate cases, the best we are able to do is to use existing data to ameliorate the bounds on the violating parameters. The last work of Bailey and Kostelecky [27] is dedicated to the pure gravity sector of the SME and many experimental setups to look for Lorentz violation are proposed. In a way, that paper can be seen as a turning point. The message there seems to be “As the electromagnetic sector is giving no positive results, let us now turn our attention to the gravity sector”.

To our knowledge, this is the state of the art. The reviewer’s job could safely stop here but, while doing it, we had the chance to take a step back

¹¹These numbers should be taken with some care, as the scope here is to illustrate the mechanism of amplification of Lorentz violating effects at work rather than to give the most severe bounds. We are also justified in doing so here by the fact that within NCED, at present, no better constraints are obtained by including synchrotron radiation of astrophysical origin (and vacuum Čerenkov radiation) [23].

from the everyday work-schedule and we could take a look at the *grand scenario* - it is of Lorentz symmetry that we are talking here - thus some general considerations naturally came to the mind. The rest of this lecture is dedicated to that.

3 Three Questions

Here are three questions:

3.1 Why questioning a solid paradigm?

Why are we so systematically “shaking” the STR? There are only two kinds of reasons to embark oneself to turn inside out a solidly tested view of nature: theoretical or experimental. The first case (theory) reduces to the second because, although the motivations to change can be fully theoretical, in the end the new theory has to face the experiments.

When we learned the STR we also learned how compelling were the *experimental* evidences that forced theorists to re-think the Galilean/Newtonian paradigm. Today this is not the case¹². On the other hand, looking closely, the argument of having compelling *theoretical* motivations presents a peculiarity that deserves consideration. The logic is as follows: If a theory claims to describe nature than it must come under the judgment of the experiments. It must provide predictions for precise signatures so that the theory itself can be proved or disproved. The SME, the NCFTs and the other approaches to Lorentz violation are surely taking the road of experiments, there is no doubt about that and it is a most welcome fact. But, in our view, the underlying motivations behind the search for Lorentz violation are in ST. This is more evident for the SME or for the NCFTs *à la* Seiberg-Witten, but more loosely speaking it can be said of the other approaches too. This leads straight to our answer to the question “why questioning STR”: we are questioning it because the dominant theory at our disposal (ST) is *somehow* telling us

¹²Another way of looking at the historical development of STR is to say that a *wrong* theoretical approach (the Galilean/Newtonian) pushed for experimental findings, such as that of a luminiferous aether, that *never came*. These *non-findings* where the experimental basis on which STR was founded. When put it this way the sentence in the text above should end with a question mark.

to do that. The reason why the (deep) theoretical motivations behind the search for Lorentz violation have a logical loophole is that: if *no signs* of violations are found this would *not* affect ST. In the negative case the SME would probably be left apart, but nothing at all would happen to ST.

It is true that, strictly speaking, ST is not necessary to write down the SME, as explicitly shown by its inventors Colladay and Kostelecky [7], and by many authors [8]. But, while this has a pleasant outcome as for the model independence and generality of certain results, on the other hand it is clear that the motivations to build up the model in the first place lay with ST. Similarly, the whole path from noncommuting coordinates till noncommutative gauge theories can be taken without mentioning the word “string” (see, e.g., [10]). Nonetheless, it was the link to ST provided by Seiberg and Witten [9] that made NCFs’ fortune as viable candidates for Lorentz violation. In a more loose sense it can be said that also the other approaches are permeated by concepts and ideas originated in or promoted by ST (such as a fundamental length/energy scale and nonlocality).

Thus, our answer to the question immediately turns on a lightspot on the very special status of ST: it leads the research in particle physics by inspiring, one way or the other, the new directions of investigation that, sometimes, reach the arena of experimentally testable scenarios, but ST itself never gets so involved with its “by-products” to the extent of being proved false¹³. This is very singular, and we do not know of any other case like that in science. To use a simplifying image: it is as if ST gets *close* to the border between theory and phenomenology, leaves there the results of its speculations and leaves to others to write down things in a form suitable for testing, but then these models are *no longer part* of ST. Another question then comes out of the first question: is ST a *physical* theory? This is a very delicate (or rough?) question to ask. We should soon try some speculations. Before doing so let us close this subsection by further clarifying our own view on the search for Lorentz violation.

Despite the lack of experiments and despite the absence of compelling theoretical reasons, for us this search still represents an important chance for a fresh rethinking of fundamental issues in particle physics - the most

¹³It is expected that, for consistency, positive outcomes of experiments, for instance in Lorentz violation, will not be taken as a proof (direct or indirect) for the experimental soundness of ST.

important of all being the symmetry principles. This way, if we are lucky, we might discover by unsuspected means where and if the “mistake” is hiding. By “mistake” here we mean that prejudice we are enforcing on our view that lead us too “far away”. It is a particularly welcome circumstance that is the community of theorists and experimentalists together that is facing these issues.

3.2 Is ST a physical theory?

This is a difficult question. We could measure how difficult it is by showing how spread between “Yes” and “No” is the plot of the answers physicists would give. There would be straight “Of course it is not”, and straight “Of course it is”. Most interestingly, there would be a blur phase of answers where the word “physics” would start changing its meaning from the original one - i.e. of an experimental science as we learned it at school - towards something less and less definite. This last class of answers (containing the “Yes”) could be the starting point for a serious discussion involving scientists and philosophers that, in our opinion, is much needed today. One way of attacking the problem (because this is a problem) would be to invoke Bridgman’s operationism [1] and see in which of its class ST would fit. Needless to say, according to Bridgman’s criteria, ST is not a physical theory. Nonetheless, more care would be needed because Bridgman’s criteria are surely not infallible and they were invented in a different era of particle physics. On top of that, we are only amateur philosophers hence unable to discern among the subtleties of *logical coherence* sometimes invoked by ST to justify its existence. Thus, we are getting too far away without a definite answer. Let us try something else.

Let us try attacking the problem by talking about a *string theorist’s*¹⁴ trajectory: Alan Kostelecky’s. To many Kostelecky is the man of Lorentz violation. He started off his career as a string theorist but of a special kind. Reading the papers he co-wrote on Lorentz violation in ST and the seminal ones on the SME one clearly notices that even before moving fully into the realm of experimentally verifiable (or falsifiable) ideas he had the (sane) attitude of a theorist with an eye (or even two) to the experimental arena.

¹⁴I was inspired in doing so by David Tong (at that time a fellow postdoc at MIT) who used to say something like “My goal is to eventually obtain an experimental prediction from string theory or, at the very latest, from a *string theorist*.”

There is a - probably unnoticed - sentence in the seminal paper on the SME that brings us a step forward towards the answer we are looking for: In the Introduction of the second entry of Reference [7] it is described in words the mechanism of spontaneous breaking of Lorentz symmetry within the higher dimensional ST. There Kosteletsky and Colladay call the four space-time dimensions *physical*. This implies that the other (twentytwo or seven or whatever) dimensions are considered there *un-physical*. So here we have at least part of the answer to our question (“Is ST a physical theory”): according to a string theorist that part of string theory that studies “phenomena” outside the four dimensions is not physics¹⁵.

To make full justice to Bridgman we should ask the same question we asked for ST for other theories/concepts available today in theoretical particle physics. These include Supersymmetry (SUSY) and its descendants, Extra Dimensions, Noncommutativity *à la* Connes, Loop Quantum Gravity, not to talk about models nowadays out of fashion such as the Grand Unification models, etc. Surely, the discussion among scientists and philosophers we evoked earlier should scrutinize those ideas as well. Nonetheless, we make three points here: First, ST is the *dominant* theory (as we think we proved in the case in point of the search for Lorentz violation) and as any good regent has to fully take the burden that goes with the honors. Second, most of (or all) the concepts and ideas above enumerated are somehow included into the “all encompassing” ST. Third, we were motivated by our investigations of the philosophical/epistemological reasons behind the search for Lorentz violation and we simply found ST behind it.

3.3 How about SUSY?

SUSY surely has its place among the ideas/theories waiting for an answer about its physical relevance. Nonetheless, physicists have to move fast and before the problem is fully solved (it might take forever...) one might try to take shortcuts. As said before, in our view, the search for Lorentz violation is very welcome exactly because it might serve the scope of changing in an unsuspected fashion ideas that were on the table. One of these ideas could be SUSY.

¹⁵As a byproduct, we also solved Tong’s problem of obtaining experimental predictions from a string theorist: ask Alan Kosteletsky.

Already Berger and Kostelecky [28] have investigated, within the SME, the effects of Lorentz violation on SUSY and found that a (modified) SUSY algebra can be written. Similarly, the effects of noncommuting coordinates on SUSY has been considered [29]. What if we take a step back and look into the no-go theorems [30] with the assumption that the spatiotemporal group is no longer ISO(3,1)?

Acknowledgments

It is my pleasure to thank the organizers of DICE2006, especially Thomas Elze, for inviting me. I also thank Ugo Senatore of the National Monument Library of Badia di Cava de' Tirreni in Italy, for providing an inspiring environment for the preparation of this lecture.

References

- [1] Bridgman P W 1927 *The Logic of Modern Physics* (New York: Macmillan)
- [2] Mach E 1977 *La Meccanica nel suo Sviluppo Storico-Critico* (Torino: Boringhieri) Italian translation from the original ninth German edition of 1933 (first edition 1883). The critical view of STR is made explicit in the Foreward to the ninth edition.
- [3] Mattingly D 2005 *Living Rev. Relativity* **8** 5
- [4] Heisenberg W 1957 *Rev. Mod. Phys.* **29** 269
- [5] Carroll S M, Field G B and Jackiw R 1990 *Phys. Rev. D* **41** 1231
- [6] Kostelecky V A and Samuel S 1989 *Phys. Rev. Lett.* **63** 224
- [7] Colladay D and Kostelecky V A 1997 *Phys. Rev. D* **55** 6760; 1998 *Phys. Rev. D* **58** 116002
- [8] Bluhm R 2005 Overview of the SME: Implications and Phenomenology of Lorentz Violation *Preprint* hep-ph/0506054
- [9] Seiberg N and Witten E 1999 *J. High Energy Phys.* **09** 032

- [10] Madore J, Schraml S, Schupp P and Wess J 2000 *Eur. Phys. J. C* **16** 161
- [11] Minwalla S, van Raamsdonk M and Seiberg N 2000 *J. High Energy Phys.* **0002** 020
- [12] Balachandran A P, Pinzul A and Qureshi B A 2006 *Phys. Lett. B* **634** 434
- [13] Mariz T, Nascimento J R and Rivelles V O 2006 Dispersion Relations in Noncommutative Theories *Preprint* hep-th/0609132
- [14] Amelino-Camelia G 2002 *Int. J. Mod. Phys. B* **11** 1643; *Int. J. Mod. Phys. D* **11** 35
- [15] Magueijo J 2003 *Rept. Prog. Phys.* **66** 2025; Magueijo J and Smolin L 2003 *Phys. Rev. D* **67** 044017
- [16] Coleman S and Glashow S L 1999 *Phys. Rev. D* **59** 116008
- [17] Carroll S M, Harvey J A, Kostelecky V A, Lane C D and Okamoto T 2001 *Phys. Rev. Lett.* **87** 141601
- [18] Iorio A and Sykora T 2002 *Int. J. Mod. Phys. A* **17** 2369
- [19] Guralnik Z, Jackiw R, Pi S-Y and Polychronakos A P 2001 *Phys. Lett. B* **517** 450
- [20] Castorina P, Iorio A and Zappalà D 2004 *Phys. Rev. D* **69** 065008
- [21] Jackson J D 1975 *Classical Electrodynamics* (New York: John Wiley and Sons)
- [22] Chaichian M, Sheikh-Jabbari M and Tureanu A 2001 *Phys. Rev. Lett.* **86** 2716
- [23] Castorina P, Iorio A and Zappalà D 2005 *Europhys. Lett.* **71** 912
- [24] Altschul B 2006 *Phys. Rev. Lett.* **96** 201101
- [25] Montemayor R and Urrutia L F 2005 *Phys. Lett. B* **606** 86

- [26] Jacobson T, Liberati S and Mattingly D 2003 *Nature* **424** 1019
- [27] Bailey Q G and Kostelecky V A 2006 *Phys. Rev. D* **74** 045001
- [28] Berger M S and Kostelecky V A 2002 *Phys. Rev. D* **65** 091701
- [29] Rivelles V O 2004 *Nucl. Phys. Proc. Suppl.* **127** 63
- [30] Coleman S and Mandula J 1967 *Phys. Rev.* **159** 1251